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PROBABILISTIC STORM SURGE HAZARD ASSESSMENT FOR A LARGE INLAND WATERBODY

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ABSTRACT

Extreme storm surges on large inland water bodies can constitute a significant hazard for low-lying vital structures. This study outlines a probabilistic approach for evaluating extreme surges on a large inland water body. A deterministic screening analysis is performed by estimating a maximum credible surge level. The screening is used to determine whether a detailed probabilistic analysis is required. The probabilistic analysis involves a detailed consideration of the available atmospheric and water level data to produce hazard curves in areas of interest. The overall methodology includes consideration for diverse peer review strategies as well as a thorough analysis of the sources of epistemic and aleatory uncertainty.

The in-depth probabilistic analysis provides a robust framework for decision-making, and provides the necessary input to a quantitative vulnerability analysis.

INTRODUCTION

Extreme storm surges can constitute significant flooding hazards for coastal locations, including locations on the coast of large lakes. This paper outlines methodology for performing a Probabilistic Storm Surge Hazard Assessment (PSSHA). A probabilistic storm surge hazard assessment provides a basis for quantitative vulnerability analysis of potentially affected Structures, Systems, and Components (SSCs). The method supports a detailed hazard analysis, containing components such as,

- A deterministic screening analysis,
- A detailed probabilistic analysis,
- Evaluation of uncertainty (epistemic and aleatory), and
- In process and overall peer review (by Subject Matter Experts [SMEs] and Probabilistic Risk Assessment [PRA] experts).

After outlining the methodology, an example study is provided for an area on the shoreline of Lake Huron. For the example study, the deterministic screening analysis consisted of estimating a maximum credible surge level, representing a conservative upper bound for storm surge levels. This level was used to determine whether a probabilistic analysis was required. The probabilistic analysis resulted in a family of hazard curves that relate surge levels to Annual Exceedance Probabilities (AEPs). The example study involved a novel method for accounting for paleo lake level data.

METHODOLOGY

The PSSHA methodology proposed in this study is summarized as follows (Figure 1):

- ***Hazard Identification***: The identification of hazard is often a straightforward process (e.g., inland riverine sites are not likely subject to storm surge hazards). However, the hazard identification process is important, and the documentation of the hazard identification process should be peer reviewed.
- ***Hazard Screening***: The screening analysis is the first step for evaluating identified hazards for a site. Screening analyses should involve demonstrably conservative assumptions and input

parameters. This often takes the form of a conservative deterministic bounding analysis (e.g., a hydrodynamic model with conservative input parameters). However, highly conservative probabilistic analyses may also be considered appropriate for some applications (subject to peer review).

- ***Determine the Appropriate Level of Probabilistic Flood Hazard Assessment (PFHA)***: For hazards that do not screen out during the screening process, a PFHA should be performed (i.e., a PSSHA). However, the specific level of effort/detail associated with the PSSHA should be appropriate to the specific project requirements and intended use of the PSSHA results. The PFHA level should be determined with input from the applicable stakeholders as well as SMEs and PRA experts who can give insight as to what level of analysis will provide the desired results.
- ***Data Gathering and Probabilistic Methods***: Data gathering is an iterative process which both informs and is informed by the choice of probabilistic methods. For example, for storm surge analysis there are at least two different approaches that can be followed, and the choice of approach depends (at least in part) on the availability of data:
    - **Approach #1**: This approach involves hydrodynamic modelling of storm surge. Storm parameters would be represented by probability density functions (i.e., separate stochastic models for radius of maximum wind, storm speed, etc.). A large number of synthetic storms would be developed to support a Monte Carlo-type analysis for generating a joint probability hazard curve for water level. This type of analysis is outlined in Toro et al. (2010).
    - **Approach #2**: This approach is based on historic and paleo water level data rather than atmospheric forcing data. Probabilistic analysis is performed directly on the water levels to compute hazard curves for total water level.

  The details of the probabilistic analysis should be developed and peer reviewed to ensure that they address all the project-specific requirements in a technically sound manner. The analysis should involve individual stochastic models for each variable and a method for combining the effects of the individual variables in a joint probability analysis. Correlations and dependencies should also be accounted for.
- ***Shoreline Interaction Analysis***: The shoreline interaction analysis evaluates the flow of inundating water around structures, along with the associated effects. While the physical presence of water (i.e., a flood depth or elevation) is the most obvious hazard due to storm surge, the secondary effects (e.g., hydrostatic forces, hydrodynamic forces, or debris impact forces) may actually cause the most severe hazards to the site and must be considered. The inundation analysis should incorporate insight from on-site observations (i.e., a walkdown) to ensure that the results are credible based on field observations.
- ***Peer Review***: The level and intensity of peer review should reflect the level of the PFHA analysis (discussed above). Peer review can be carried out in several ways throughout the course of the project. In-process peer review solicits the opinions of SMEs or PRA experts throughout the course of the project. The format of the review could be a formal Expert Elicitation or a less formal process. In contrast to an in-process peer review, an overall peer review can be conducted at the end of a project. Both internal and external peer review can be performed.
- ***Evaluation of Uncertainty***: Due to the nature of the extreme events of interest for a PSSHA, it is important to perform a comprehensive evaluation of the uncertainty associated with the analysis. The uncertainty analysis should be ongoing throughout the PSSHA analysis and subjected to peer review. Uncertainty is often categorized into two separate categories, aleatory and epistemic. Aleatory uncertainty is uncertainty that is understood to be intrinsic variability in the system being studied. Uncertainty that cannot conceivably be reduced by larger datasets, better models, better science, etc. is considered to be aleatory uncertainty. In contrast, epistemic uncertainty can conceivably (though not necessarily practically) be reduced by increased understanding of the system.

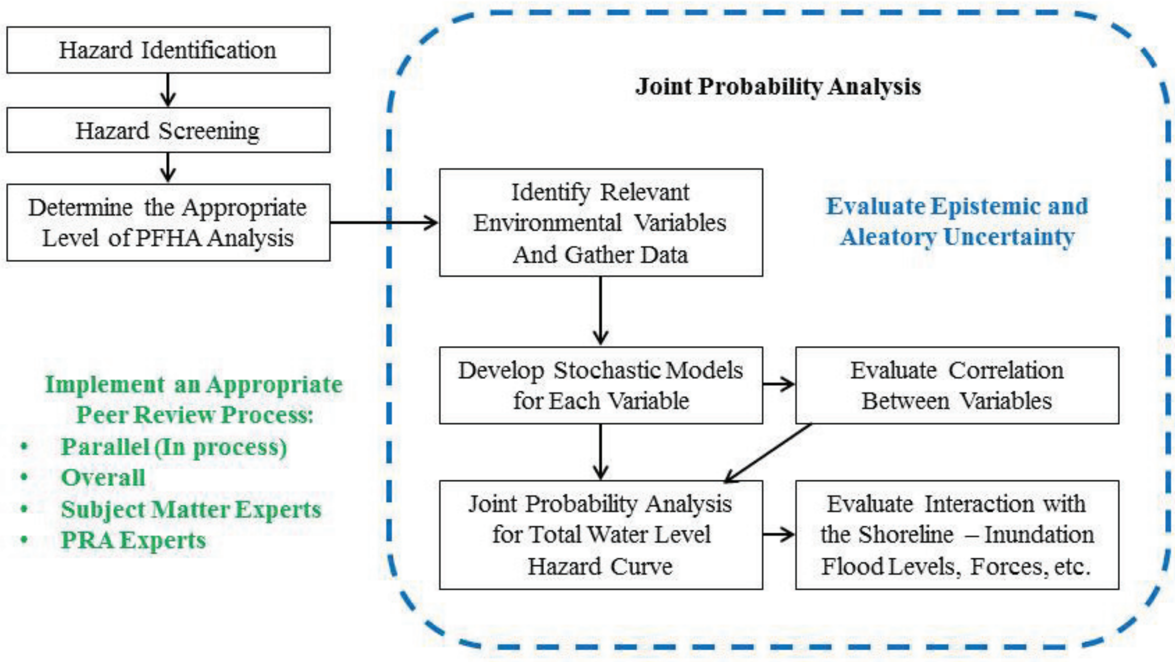

Figure 1: Probabilistic Storm Surge Hazard Assessment Methodology

EXAMPLE STUDY

The example study presented in this paper concerns an area on the shoreline of Lake Huron (Figure 2). Due to the shoreline location of the area of interest, the "Hazard Identification" process indicated that storm surge was a conceivable hazard and should be considered for a screening analysis.

Screening Analysis

A deterministic screening bounding analysis was performed to evaluate whether flooding due to storm surge is a credible hazard for the area of interest. The screening analysis involved developing a conservative hydrodynamic model to simulate storm surges (and associated wind-wave effects). The approach is summarized as follows:

- Conservative storm characterizations were developed using parameters (e.g., wind speed) obtained from various literature sources. The most conservative credible parameter values (or a range of parameter values) were chosen.
- A two-dimensional hydrodynamic model was developed with conservative model parameters (e.g., wind drag coefficients) to simulate the storm surge levels associated with the postulated conservative storm scenarios.
- Wave run-up effects were evaluated (note that the most severe wave run-up levels and forces may not correspond to the highest storm surge still water levels).

The results of this screening analysis indicated that storm surge (particularly the associated effects due to wave run-up) resulted in inundation of the area of interest.

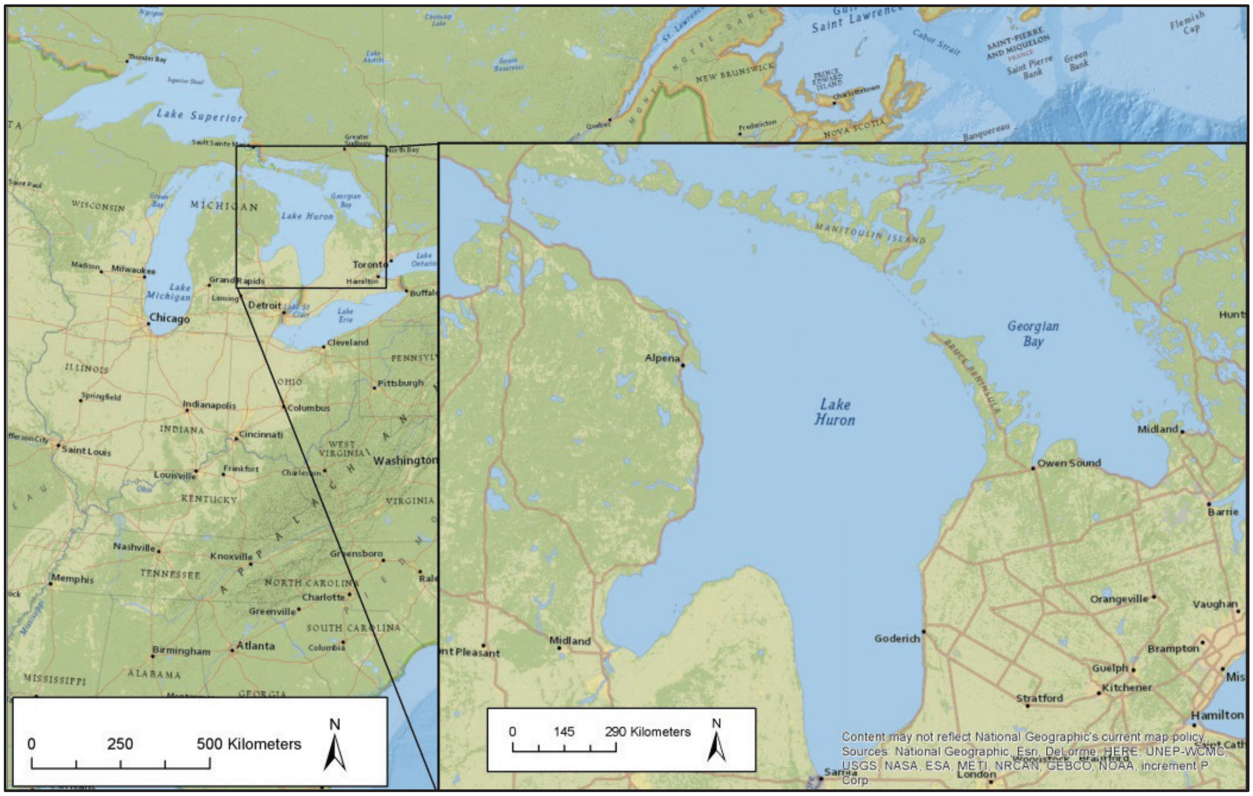

Figure 2: Study Area Location

Probabilistic Storm Surge Hazard Assessment

Based on the results of the screening analysis, it was concluded that a full PSSHA should be performed for the area of interest. The specific level of effort for the PSSHA was determined based on the project-specific requirements and the acceptable risk level that was agreed upon for the area of interest.

The initial phase of the probabilistic analysis involved additional data collection and methods selection. As discussed above, the data collection and methods selection processes complement each other. In particular, the data availability for Lake Huron played a key role in the methods selected for this analysis. A review of data sources for atmospheric storm parameters indicated that there was insufficient data to perform a detailed statistical analysis for atmospheric forcing parameters. In contrast, long records (over 100 years in some cases) of lake level gage data are available for multiple locations on Lake Huron. Consequently, **Approach #2** (as outlined above) was considered the most appropriate method for this study.

This analysis was conducted using the following methodology (Figure 2):

- Identify relevant environmental variables for probabilistic analysis (e.g., overall lake levels, historic surge levels, and wind waves) and assess availability of historical data to describe each variable.
- Develop stochastic representations for each environmental variable.
- Assess the correlation and dependence between the environmental variables.
- Perform Monte Carlo simulations to combine the variables and determine the joint probability curves for storm surge levels (i.e., the hazard curve).
- Perform an evaluation of the uncertainty associated with the probabilistic analysis.
- Engage with an appropriate level of peer review (e.g., subject matter experts).

Environmental Variable Selection and Data Pre-processing

Publically available water level data for Lake Huron were surveyed. The two nearest gages to the area of interest were considered the most applicable for describing relevant storm surge events. The data from both gages were used for this analysis. Individual surge events were "separated" from the background lake level, and an annual maximum series was then created for probabilistic analysis from the largest surge events at each gage station.

Data from the Harbor Beach gage were used to characterize the background lake level variability (i.e., effects due to seasonal fluctuations rather than individual storm events). The Harbor Beach gage has the longest record of any gage on Lake Huron (1860 – present).

Paleo lake level data (Figure 3) were obtained from Sellinger (2006) and Baedke and Thompson (2000). The paleo lake level reconstructions from Baedke and Thompson (2000) extend back further than 4000 years BP (Figure 3). However, the lake levels earlier than approximately 4000 BP are significantly higher than the present lake levels, indicating some sort of change in the watershed configuration. This creates a non-stationary statistical system, such that the data before 4000 BP are not applicable for present day probabilistic analysis. Consequently, only 4000 years of paleo lake level data were used for this analysis.

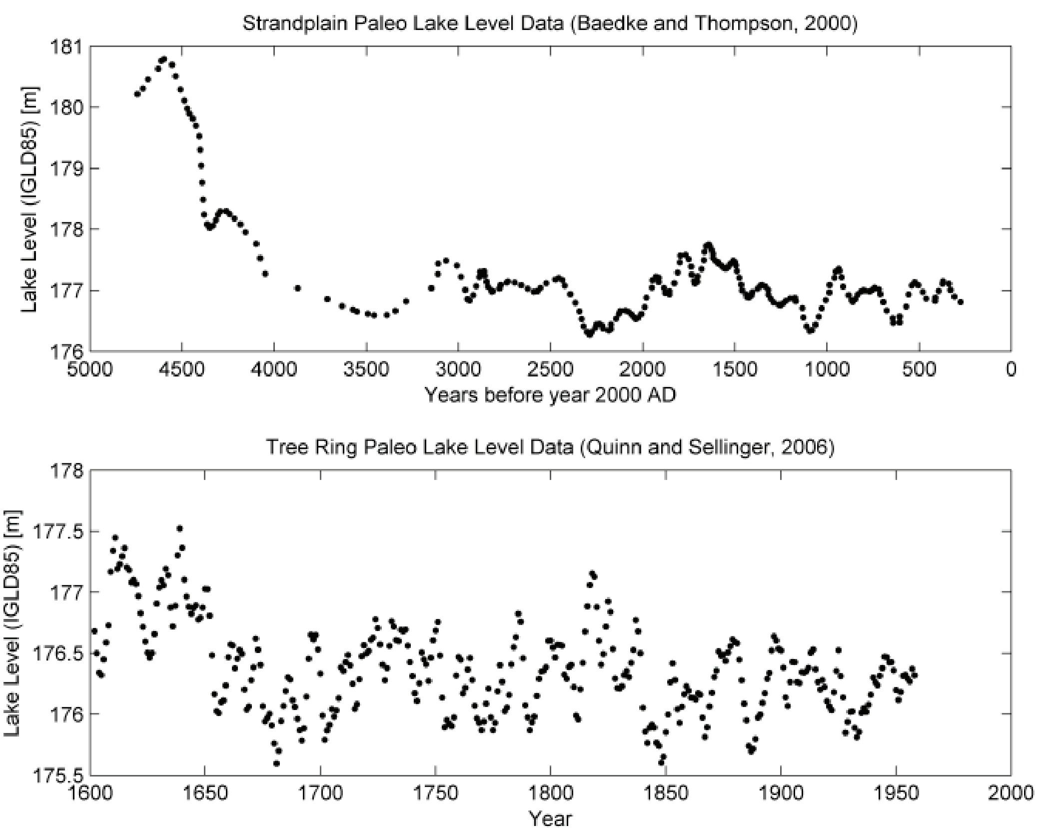

Figure 3: Paleo Lake Level Data

Development of Stochastic Models

Stochastic models were developed separately for describing storm surge amplitudes and mean lake levels (in this context the term "mean" is used in a broad sense as lake levels representing the entire lake in contrast to levels at particular locations that are affected by atmospheric forces). The amplitude of a storm surge event above the mean lake level was characterized by fitting multiple probability distribution functions to the series of annual maximum storm surge events. Four probability distribution types were considered based on general distribution shapes and applicability for storm surge as determined from prior studies (Pearson Type III, Log-Pearson Type III, Log-normal, and Generalized Extreme Value). Additionally, two different methods were considered for defining the skew coefficient for the Pearson Type III and Log-Pearson Type III distributions: computing the skew coefficient from the data, and using a so-called "regional" skew coefficient based on other storm surge studies for Lake Huron (e.g., USACE [1988]). With two water level gage stations as input, this resulted in 12 different probability distribution functions.

The goodness-of-fit for each probability distribution function was evaluated, and each distribution was assigned a weighting factor based on how well it fit the historic data. These weighting factors represent the contribution of each probability distribution function to a weighted mean probability distribution function. Based on project-specific criteria, it was determined that the mean curve was sufficient for use in the analysis (other applications may require the use of other fractile quantities). The weighted mean probability distribution function accounts for the different distribution functions considered, as well as the different ways of assigning the skew coefficient to the Pearson Type III and Log-Pearson Type III distributions.

The weighted mean probability distribution function also accounts for the two data sources for the surge level data by assigning relative weights to the two data sources. It was determined (through a hydrodynamic modelling sensitivity study not discussed in this paper) that surges at one of the gage stations provided a better representation of the location of interest (in terms of magnitude and exceedance probability) than the other gage station. Consequently, the station that fit better was assigned a weighting factor of 0.6, while the other station was assigned a weighting factor of 0.4.

As noted above, a stochastic model for the background lake level was developed separately from the characterization for storm surge events. Several sources of data were available for describing the mean lake level (two sources of paleo lake level data, mean monthly lake level data from the Harbor Beach gage, and higher resolution lake level data from the local gages). The range of data types and data timescales defied traditional statistical analysis, i.e., it would be difficult to combine these datasets in such a way that they could be meaningfully described by a single probability distribution function.

Because of the difficulty with applying "traditional" probability distribution functions for describing mean lake level, a methodology was developed for this study that represents the lake level variability in terms of amplitude spectra (i.e., by taking a Fast-Fourier transform of each dataset). The key observation that underpins this method is that each of the available datasets contains different information about the lake level variation. The paleo lake level data contain information about long-term data fluctuations (e.g., multi-decadal cycles). Whereas, the monthly mean lake level data contain information about shorter fluctuations (e.g., seasonal variation) that are not captured in the paleo data.

A Fast-Fourier transform was computed for each dataset. The corresponding amplitude spectra (amplitudes representing lake level fluctuations at a particular frequency) were pieced together into a composite with each component spectra contributing the frequency components that represent the timescales of information contained in the respective dataset. The composite spectrum was used to generate synthetic lake level data with the same characteristic fluctuations as the historic data (as described by the combined datasets used for this analysis). A time series of synthetic lake level data was generated by essentially performing an inverse Fast-Fourier transform with the composite amplitude spectrum and random phases. Individual lake level data points can be generated by applying the spectral amplitudes to cosine functions with randomly generated phases.

Several different lake level characterizations were considered as sensitivity analyses to account for the uncertainty as to which datasets should be used to generate which spectral components, i.e., should 20 year lake level fluctuations be characterized by paleo data or mean monthly data? Either dataset could be justified, so a sensitivity analysis is appropriate to quantify the uncertainty associated with this method.

In addition to the lake level analysis completed with the Fast-Fourier transform method, an analysis was completed (not presented in this paper) that applied probability distributions to individual lake level datasets. As mentioned above, it is difficult to perform a traditional probabilistic analysis for water level in a manner that includes all of the available data. However, each individual lake level dataset can be fit with traditional probability distribution functions. This analysis was completed separately (including an evaluation of associated uncertainty) and provided comparable results.

Joint Probability Analysis (Including Correlation and Dependence)

The two variables under consideration (individual storm surge event amplitudes and the mean lake level) were evaluated to determine whether there was a statistical correlation. For example, if it could be established that higher surge levels generally occur coincident with higher lake levels, this correlation would be important to incorporate in the analysis.

A common test for correlation is to compute a covariance matrix between two datasets (Hosking and Wallis, 1997). The off-diagonal elements represent a quantification of the correlation between the datasets. For this analysis, a covariance matrix was computed, which demonstrated that there was no correlation between surge levels and lake levels. Consequently, these variables were considered to be independent for the remainder of the study.

The two stochastic models developed (for surge amplitudes and lake levels) provide probabilistic descriptions of each variable. To determine the joint probability distribution, large synthetic datasets were generated to represent "millions of years" of annual maximum surge levels (i.e., Monte Carlo simulation). Each synthetic annual maximum surge level (generated from the mean surge level distribution) was paired with a randomly generated synthetic lake level. Ten million data points were generated for each simulation. The resulting total lake levels (surge plus mean lake level) were sorted for plotting (Figure 4) to demonstrate the probability of exceedance for low probability lake levels.

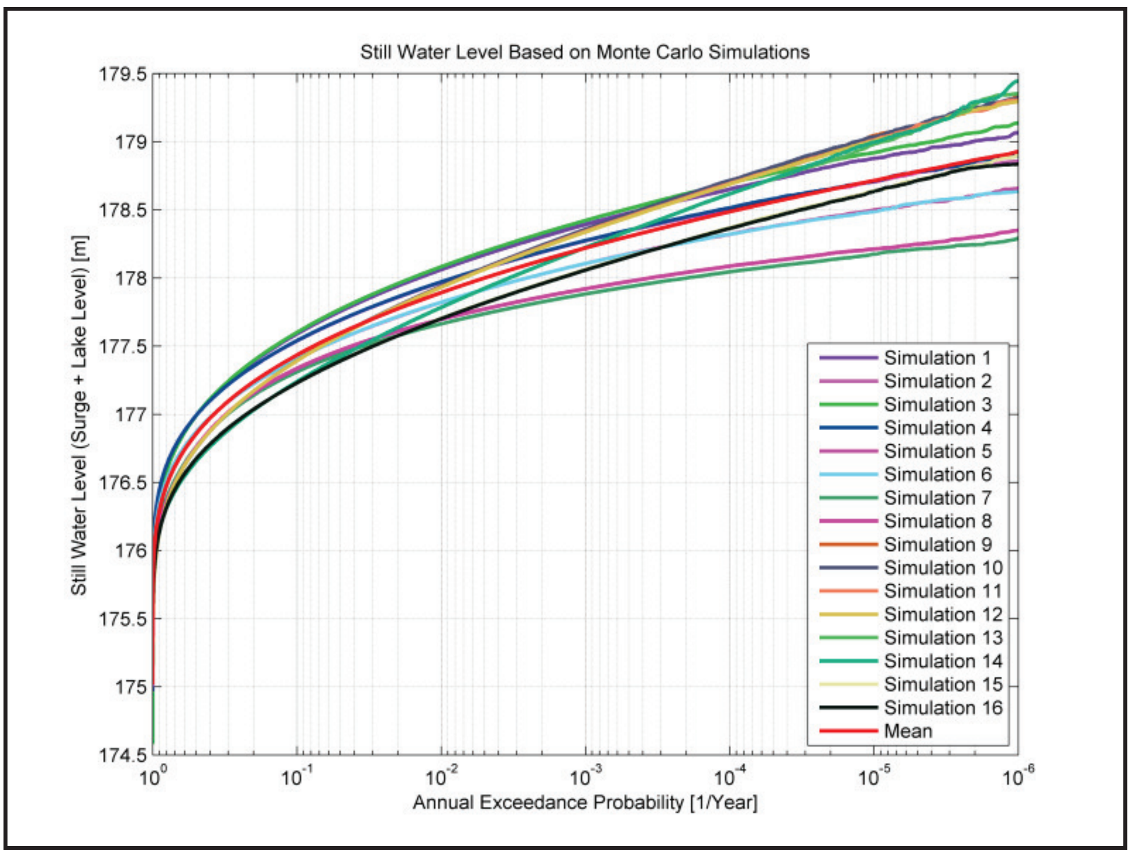

Figure 4: Combined Lake Level Probability of Exceedance Curves

Various simulations were performed with different parameterizations of the lake level spectral representation. Subsequent to the Monte Carlo simulations, a weighted average lake level curve was computed to represent the mean hazard curve in the area of interest. Note that while this example study discusses the "mean" hazard curve, other fractile curves could be computed based on the required risk levels agreed upon by stakeholders and the peer review team. Additional fractile curves also help to quantify the uncertainty.

As a way of verification, the results of this probabilistic analysis were compared to the 100-year surge level reported in publically available government studies, which accounts for both surge level effects and the background lake level variability. The 100-year surge level is reported as 177.6 m IGLD85, which is approximately 0.3 m lower than the value reported in this study. This difference is likely due to the inclusion of paleo lake level data in this present study, which indicates greater fluctuations than have been observed in the period of record.

Evaluation of Uncertainty

Throughout the analysis outlined above, there are various sources that contribute uncertainty to the storm surge hazard curve. It is critical that a probabilistic analysis be accompanied by a rigorous review of the associated aleatory and epistemic uncertainty. Whenever possible, steps should be taken to quantify/reduce the uncertainty in the analysis to obtain better results (e.g., using Bayesian methods, logic trees, etc.). The peer review process provides important input to the evaluation of uncertainty. Whether through an in-process peer review or an overall review subsequent to the analysis, input from subject matter experts and PRA experts is valuable for understanding the uncertainty associated with a PFHA analysis. The following paragraphs summarize the uncertainty analysis associated with the example study.

Paleo lake level data: The methods for obtaining paleo lake level data involve diverse assumptions, including models of glacial isostatic adjustments (i.e., uplift of the land around the Great Lakes due to glacier melt). The potential uncertainty in these methods is considered as epistemic uncertainty (i.e., uncertainty due to lack of scientific knowledge). The analysis was conducted both with and without paleo lake level data, a sensitivity study that helps to quantify the uncertainty associated with the analysis. Additionally, two different sources of paleo lake level data are used, which reduces the contribution of uncertainty from any one source.

Probability Distribution Functions: The choice of probability distribution type affects the prediction of extreme values. Since it is not clear *a priori* which type of probability distribution function (e.g., Generalized Extreme Value or Pearson Type III) is most appropriate, multiple distributions were considered. Distributions that provided a better fit to the data were given a higher weight in the final weighted mean average surge hazard curve.

Probability Distribution Function Parameters: Due to the finite sample size, there is uncertainty in computing the parameters for each probability distribution function. Additionally, there are multiple statistical methods for obtaining probability distribution function parameters. There is uncertainty involved in determining what method provides the best estimate.

Other Sources of Uncertainty: Many other sources of uncertainty were evaluated, including:

- Measurement tolerances in the lake level data,
- Determining which data stations are more applicable for the area of interest,
- Determining the best method for evaluating goodness-of-fit,
- Methods for characterizing the background lake level (i.e., traditional statistical analysis versus the Fourier analysis method applied in this study),
- Selection of frequency ranges for the Fourier analysis method applied for characterizing lake levels.

Uncertainty was evaluated by applying multiple methods and sensitivity analyses, with input from subject matter experts (i.e., peer review) where possible to ensure that there were no "cliff-edge" effects. A probabilistic analysis that applies multiple methods (with weighting factors) produces a hazard curve that is not sensitive to any particular input or assumption. This reduces uncertainty in the overall analysis because the final result is not controlled by a single factor. Rather the resulting hazard curve is a stable average of many different methods, models, inputs, etc. A portion of one of the logic trees used for the epistemic uncertainty analysis is shown in Figure 5. The logic tree represents the multiple characterizations considered and the weighting factors applied to each characterization.

Storm Surge Event Amplitudes				
Frequency Curve Under Consideration	**Gage location for Storm Surge Analysis**	**Type of Probability Density Function**	**Skew Coefficient Method (Pearson Type III and Log-Pearson Type III only)**	**Cumulative Subjective Weight**
Storm Surge Level at the Area of Interest	Data Station #1 (0.4)	Generalized Extreme Value (0.2)		0.0800
		Log-Normal (0.2)		0.0800
		Pearson Type III (0.4)	Skew based on data (0.4)	0.0640
			Regional skew (0.6)	0.0960
		Log-Pearson Type III (0.2)	Skew based on data (0.4)	0.0320
			Regional skew (0.6)	0.0480
	Data Station #2 (0.6)	Generalized Extreme Value (0.2)		0.1200
		Log-Normal (0.2)		0.1200
		Pearson Type III (0.4)	Skew based on data (0.4)	0.0960
			Regional skew (0.6)	0.1440
		Log-Pearson Type III (0.2)	Skew based on data (0.4)	0.0480
			Regional skew (0.6)	0.0720
			TOTAL	1.0000

Figure 5: Portion of a Logic Tree (Epistemic Uncertainty Model)
NOTE: Numbers in parentheses indicate weighting factors.

Peer Review

The example PSSHA study was subject to internal in-process peer review by SMEs and external overall peer review by PRA experts and the applicable regulatory body. The peer review process provided insight into the decisions made throughout the analysis, including the weights assigned for the discrete probability epistemic models (i.e., branches of the logic trees).

CONCLUSIONS

A methodology was outlined for performing a Probabilistic Storm Surge Hazard Assessment (PSSHA). The methodology includes consideration for hazard identification and hazard screening, as well as a detailed probabilistic analysis and evaluation of shoreline effects. Peer review methods are also discussed, along with considerations for accounting for both epistemic and aleatory uncertainty.

Results are presented for an example study. A deterministic screening analysis was performed with a hydrodynamic storm surge model. Based on the results of the screening analysis, it was determined that a full PSSHA should be performed. The PSSHA study involved a detailed probabilistic analysis of lake water levels (including consideration for paleo lake level data), an evaluation of uncertainty, and a peer review. The PSSHA produced a family of hazard curves that relate storm surge effects to Annual Exceedance Probabilities.

The storm surge hazard curves for water level provide the bases for evaluating other shoreline effects such as hydrostatic forces, hydrodynamic forces, and debris impact loadings. Evaluation of these factors is critical to understanding the full effect of the storm surge hazard at a site.

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